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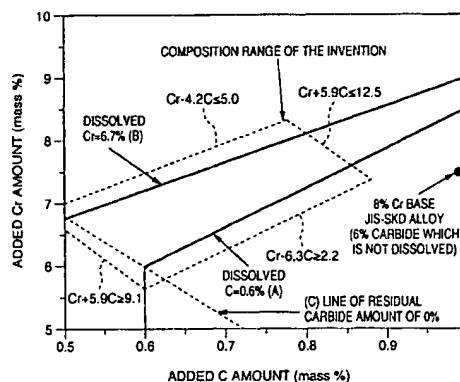
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(54) **Tool steel with excellent workability, machinability and heat treatment characteristics, and die using same**

(57) Provided is a tool steel which contains, by weight, C and Cr in both of which  $(Cr + 5.9 \times C)$  is 9.1 to 12.5,  $(Cr - 4.2 \times C)$  being not more than 5 and  $(Cr - 6.3 \times C)$  being not less than 2.2. In addition to these elements, this tool steel preferably contains 0.1 to 0.6% Si, 0.1 to 1.2% Mn, at least one of Mo and W of 0.6 to 1.25% in total in terms of  $(Mo + 1/2W)$ , less than 0.5% V, not more than 0.12% S, not more than 100 ppm of Ca, and the balance Fe and incidental impurities. Moreover, in this tool steel, the Cr segregation range in matrix after hardening is not more than 1% by weight, or the maximum tempering hardness by tempering at a temperature of not lower than 500°C is not less than 57 HRC, or a size variation due to heat treatment occurring by tempering at a temperature of not lower than 500°C is not more than 0.1% relative to the size measured just before hardening in terms of linear expansion coefficient and a size variation due to heat treatment by tempering at 490°C is not more than 0. Provided is also a die made by tempering the steel of the invention to a hardness of not less than 55 HRC and cutting the steel.

FIG.2



**Description****BACKGROUND OF THE INVENTION**5 **Field of the Invention**

[0001] The present invention relates to a tool steel used in dies for the blanking, punching, bending, drawing or trimming of steel sheets used in automobiles, home electric appliances, agricultural implements, etc.

10 **Description of the Prior Art**

[0002] Automobile makers, etc., have carried out cost reductions in every field to be winners in cost competitions and to make profits. These fields include dies and various cost-reduction measures have been taken to shorten steps for manufacturing products formed by means of press dies, to reduce the number of steps for producing dies, and further to develop methods of working dies and tools.

[0003] In such dies, materials for conventional dies and particularly for cold working dies are required to contain a large amount of carbides to obtain wear resistance and further to contain high Cr contents to obtain excellent hardenability and toughness. For example, high-carbon, high-chromium-base steels, such as SKD11, which is an alloy tool steel specified in JIS G 4404, are used for these dies.

[0004] However, in the recent tendency, it is intensively demanded to more reduce the number of steps of cutting work. In forming technique, the cutting work which is essentially high in cost has become more high in cost because of progress in plastic working and, to resist this trend, new technologies have been developed as can be seen in the development of CBN and coating tools, the emergence of high-speed cutters, the advance of an NC algorithm, etc. In response to this current of technologies, as tool steels with improved machinability there are free-cutting tool steels which are obtained by adding sulfur to a chemical composition similar to that of SKD11. However, since there are various kinds of cutting works, it is impossible to meet such various cutting manners and cutting conditions as end milling, milling, drilling, etc. simply so far as the mere adding of sulfur is concerned.

[0005] Moreover, according to reports which arrive one after another, the emergence of high-speed cutters enables the working of 60 HRC materials to be performed in a hardened and tempered state. However, cutting is still difficult although rough working, etc., are possible. This is because the machinability of high-hardness materials can not always be improved simply by adding sulfur in the above SKD11 and because it is necessary to reduce the amount of carbides itself.

[0006] In addition to the problems as to the cutting work, size variations due to heat treatment also pose a problem. This is because when size variations due to heat treatment are great, it is necessary to have large machining allowances, with the result that the number of steps of finishing increases. Although JIS-SKS3 is a low-alloy tool steel and has much better machinability than JIS-SKD11, it has bad hardenability and oil hardening is necessary, so that warping is apt to occur in SKS3. Further, in a 8% Cr-base die steel developed in the 1980's, size variations due to heat treatment and deformation with the lapse of time (secular change) are apt to occur although this steel has good hardenability. As a result, JIS-SKD11, which is more difficult to machine, is better regarding the size variations which occur due to heat treatment.

[0007] Further, in dies used for the blanking, punching, bending, drawing, trimming, etc. of steel sheets, cracks have come to occur frequently during the forming of the shapes of work pieces which change three-dimensionally, and there has been a growing need for weld reparability, etc. In other words, it is judged from the recent trend that even when it becomes necessary to make a shape modification due to a design change which is apt to occur because of shortened periods of die fabrication than before and even when breaks and cracks occur due to severe conditions, etc. during the use of dies, weldability has become important which enables dies to be reused by repairing it.

[0008] More specifically, the conventional tool steels have advantages and disadvantages, and a tool steel that has both heat treatment characteristics equivalent to those of SKD11 and machinability equivalent to that of SKS3 is presently desired. With respect to heat treatment characteristics, in particular, it is intensively desired that a new tool steel can be put in the same heat treatment furnace as in SKD11 for the sake of the rationalization of heat treatment operation.

**SUMMARY OF THE INVENTION**

[0009] The object of the present invention is to provide a tool steel with excellent weldability, machinability and heat treatment characteristics without a deterioration in mechanical properties such as toughness.

[0010] The present inventors researched the basic conditions necessary for improving weldability, machinability and heat treatment characteristics while keeping basic mechanical properties such as toughness and wear resistance.

[0011] In conventional die materials, there has been performed such composition design as large amounts of hard

and brittle carbides are contained to regard wear resistance as important. However, because surface treatment techniques have recently advanced as means for giving wear resistance to dies, it is not necessarily needed to think much of the wear resistance of die materials themselves in comparison with that of the present. From the standpoint of crack resistance and weldability, these carbides are factors in promoting crack propagation and, therefore, it is necessary to reduce the carbides to appropriate amounts.

[0012] Next, the present inventors researched various cutting methods adopted to cut tool steels and found out that types of damage to cutting tools are broadly sorted into two: chipping-type damage and thermal damage. The inventors ascertained that a process in which these two types of damage are caused simultaneously in different places of one tool can be realized on a square end mill under specific conditions. Specifically, the present inventors ascertained that mechanical damage occurs at the cutting edge and that thermal damage occurs at the boundary where the contact thereof with the work terminates. By using this process, the inventors examined various free-cutting techniques which reduce these two damage mechanisms.

[0013] As a result, the inventors found out components and composition ranges sufficient for obtaining good mechanical properties, in particular, hardness and toughness even when the content of C, which is a basic component of tool steels, is lowered. In addition, the inventors found out that a reduction in primary carbides present in tool steels can minimize the mechanical damage. In researching various cutting methods and cutting conditions which make it possible to simultaneously realize the above two effects, the inventors have finally attained a tool steel best suited to the achievement of the effects.

[0014] The tool steel of the present invention consists, by weight, of: C and Cr in both of which  $(Cr + 5.9 \times C)$  is 9.1 to 12.5,  $(Cr - 4.2 \times C)$  being not more than 5 and  $(Cr - 6.3 \times C)$  being not less than 2.2; 0.1 to 0.6% Si; 0.1 to 1.2% Mn; at least one of Mo and W in which  $(Mo + 1/2W)$  is 0.6 to 1.25%; less than 0.5% V; and the balance Fe and incidental impurities.

[0015] In the above composition ranges, it is preferable that the C content be 0.55 to 0.75%, that the Cr content be 6.8 to 8.0%, and that the eutectic value  $Z [= 8 \times (C\%) + 0.6 \times (Cr\%)]$  be not more than 10.8. Further, it is preferable that the area ratio of carbides each having a sectional area not less than  $20 \mu m^2$  to the section of the metal structure be not more than 3%. Further, it is preferable that the area ratio of sulfides each having a sectional area not less than  $1 \mu m^2$  to the section of the metal structure be not less than 0.2%.

[0016] Moreover, in the tool steel of the present invention, Cr segregation range in matrix (which is defined by a range (%) of Cr content variation in matrix with respect to the average of Cr content) after hardening is not more than 1% by weight, or the maximum tempering hardness is not less than 57 HRC when tempering is performed at a temperature of not less than  $500^\circ C$ . The die of the present invention is fabricated from the tool steel in which a size variation due to heat treatment by tempering at a temperature of not less than  $500^\circ C$  is not more than 0.1% in comparison with the size measured just before hardening in terms of linear expansion coefficient and in which tool steel a size variation due to heat treatment by tempering at  $490^\circ C$  is not more than 0 when this steel is tempered to a hardness of not less than 55 HRC and cutting the steel.

#### BRIEF DESCRIPTION OF THE DRAWINGS

[0017] Fig. 1 is an explanatory diagram of the effect of the present invention.

[0018] Fig. 2 is a detailed view of Fig. 1.

[0019] Fig. 3 is an explanatory diagram of the behavior of size variations due to heat treatment.

#### DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0020] The tool steel of the present invention has both such heat treatment characteristics as close to those of JIS-SKD11 and such machinability as substantially equivalent to that of JIS-SKS3. Incidentally, JIS-SKD11 consists, by weight (the same applying to the following), of: 1.40 to 1.60% C, not more than 0.40% Si, not more than 0.60% Mn, not more than 0.030% P, not more than 0.030% S, 11.00 to 13.00% Cr, 0.80 to 1.20% Mo, 0.20 to 0.50% V, and the balance Fe and incidental impurities, and JIS-SKS3 consists of: 0.90 to 1.00% C, not more than 0.35% Si, 0.90 to 1.20% Mn, not more than 0.030% P, not more than 0.030% S, 0.50 to 1.00% Cr, 0.50 to 1.00% W, and the balance Fe and incidental impurities.

[0021] The details as to how the present inventors found out an improvement in this machinability is explained below.

[0022] The inventors researched composition design capable of heat treatment which is almost the same as with SKD11 in the region where the amount of carbides is reduced. Incidentally, SKD11 is a tool steel of de facto standard. The inventors adopted such a basic line as, in order to obtain the same heat treatment characteristics, components which are in a solid solution state in the matrix at the time of hardening are made similar to those of SKD11. Fig. 1 shows the whole of a composition design diagram determined by means of a thermocalculator and Fig. 2 is a composition design diagram in which the region corresponding to the present invention is enlarged. Line (A) indicates a line

(on the plane of added components) on which the same amount of dissolved C (which means carbon contained in a solid solution) as with SKD11 upon hardening is obtained. Similarly, Line (B) indicates a line of the same amount of dissolved Cr as with SKD11. The two lines are bent, which is due to the fact that residual carbides exist above Line (C) with the result that alloying elements are consumed to form the carbides, whereby dissolved elements of the matrix cannot be kept at the same levels unless the amounts of added components are increased.

[0023] The two lines (A) and (B) basically intersect with each other only in the composition of SKD11 and, therefore, it is impossible to design the same matrix composition as with SKD11 at the same hardening temperature. Nevertheless, Lines (A) and (B) approach each other in the area above Line (C) and, therefore, the matrix composition becomes close to that of SKD11. However, when the amounts of added C and Cr are increased in order to bring these lines closer to each other, the amount of residual carbides increases, promoting the tool wear of the chipping type and leading to deteriorated machinability. Further, in this case fatigue fracture becomes apt to occur regarding durability, so that the application of steels to dies in which stress concentration is apt to occur is limited. This mutually contradictory relationship was experimentally clarified, and it was found that the region in which machinability is excellent and in which the heat treatment characteristics are close to those of SKD11 is achieved in the composition range of the tool steel of the invention shown in Fig. 2.

[0024] In recent years, special importance has been placed on size variations due to heat treatment in comparison with other heat treatment characteristics. For the quality of dies, shape accuracy has recently received special attention in addition to durability, and SKD11 is valued highly also in this respect. A concept regarding the control of size variations due to heat treatment is given below.

[0025] The principle of the behavior of the size variations due to heat treatment is shown in Fig. 3. In an as-hardened state, each of crystal lattices is expanded by the carbon in a solid solution state in the martensite structure of a matrix. When the tempering temperature is raised, cementite precipitates in the low- and medium-temperature region ((A) area in Fig. 3) and the size variation comes to have a tendency to shrink. In the high-temperature region, the size variation rate reaches a maximum at a temperature which is almost the same as with secondary hardening. This maximum value occurs due to two mechanisms which occur mainly on the low-temperature side ((B) area in Fig. 3) and high-temperature side ((C) area in Fig. 3) of this maximum value. On the low-temperature side of this maximum value, the decomposition of retained austenite occurs more when the temperature is raised, with the result that a tendency toward expansion occurs. On the high-temperature side of the maximum value, the amount of dissolved C in martensite decreases due to the precipitation and aggregation of  $M_7C_3$ -base and  $M_{23}C_6$ -base carbides and, for this reason, a tendency toward shrinkage occurs.

[0026] In SKD11, its composition is such that the size variations occurring between the mechanisms (B) and (C) are suppressed while maintaining hardness with the aid of the mechanisms of (A), (B) and (C). Here lies the source of the present invention in which the matrix composition is made close to that of JIS-SKD11. For this reason, optimization is performed not only for C and Cr, which are the main alloying elements of JIS-SKD11, but also for Mo and W that control the precipitation of  $M_7C_3$ -base and  $M_{23}C_6$ -base carbides which control the precipitation of cementite, as shown in Fig. 3.

[0027] In the composition system of the invention, primary carbides do not easily crystallize in an equilibrium diagram and, therefore, a further improvement in machinability is achieved by performing quenching-and-solidifying or diffusion annealing at about 1100 to 1400°C, thus taking measures to completely remove or reduce the primary carbides.

[0028] In addition, the inventors examined the function of the adding of S with respect to the size variations due to heat treatment. As a result, they found out that the size variation due to heat treatment increase when the amount of added S exceeds 0.2%. There has so far been no such a report and the reason for this seems to be that the size variations due to heat treatment present scarcely any problem in free-cutting steel systems in which the addition of S is frequently carried out. On the other hand, it might be thought that because more amount of residual carbides exist in tool steel systems, the function of constraining size variations occurs, making it impossible to detect the effect of S on size variations. As a result of this, the inventors found out that it is necessary to make adjustments to a composition so that the content of S becomes not more than 0.2% at which the size variation is small. The amount of added S is preferably 0.005 to 0.12%.

[0029] Next, the heat treatment and surface treatment characteristics of the tool steel of the invention are described.

[0030] According to the present invention, good surface treatment characteristics are also ensured to cope with such a case as wear resistance becomes insufficient because of limited C contents. Possible kinds of heat treatment include carburizing, nitriding, PVD (physical vapor deposition) and CVD (chemical vapor deposition). In the case of CVD, treatment becomes difficult depending on the properties of a base material to be treated. In this treatment, an element to be deposited, which is vaporized at about 1000°C, is chemically precipitated on the surface of the material. For this reason, substantially similarly to the heat treatment of the material, there occur problems such as insufficient hardening and much size variation due to heat treatment.

[0031] More specifically, although hardenability, which is a representative index of heat treatment characteristics, is imparted to materials so that all kinds of heat treatment equipment may be applicable, the hardenability of the tool steel of the present invention is sufficiently good because a composition close to that of JIS-SKD11, which has good

hardenability, is used. Further, because it enhances industrial convenience to make the amount of size variation due to heat treatment during hardening and tempering equal to that of JIS-SKD11, it is important to adopt the composition area shown in Fig. 2 so that the C and Cr contents in the matrix may be closer to those of JIS-SKD11. JIS-SKD11 is also used as a gauge steel because the size variation due to heat treatment is small.

[0032] The reason why the size variation of SKD11 due to heat treatment is small is that the hardness in the high-temperature tempering region is maintained by such a method as to suppress the precipitation of cementite almost only by dissolved Cr. More specifically, in secondary-hardened steels in which Mo, W and V are positively added which are usually added in high-speed tool steels capable of high-temperature tempering, fresh martensite formed by the decomposition of retained austenite occurring during secondary hardening does not easily cause tempering shrinkage and, therefore, much size variation due to heat treatment occurs.

[0033] However, when the achievement of a similar effect is aimed by use of Cr, Cr-base carbides such as  $M_7C_3$ -base carbides precipitate rapidly in fresh martensite with the result that tempering martensitizing occurs rapidly and, therefore, the amount of dissolved C in the martensite is reduced and extreme expansion can be prevented. This is the reason why the size variation of JIS-SKD11 due to heat treatment is small. Because the size variation due to heat treatment has an effect on the amount of finishing allowance in the finishing working performed before heat treatment, they provide an important factor in influencing working efficiency just like machinability.

[0034] At any rate, by making the amounts of dissolved C and Cr close to those of JIS-SKD11, it is ensured that obtained characteristics are such that the size variation due to surface treatment (, which poses a problem in size variation due to heat treatment in the case of CVD, etc.), hardenability, hardness, and size variation occurring with the lapse of time can be regarded to be practically the same as those of JIS-SKD11. This enables the tool steel of the invention to be put to the same heat treatment furnace as with SKD11 and, therefore, the cost of surface treatment operation can be substantially reduced greatly.

[0035] The amount of dissolved C present in the austenite structure at a surface treatment temperature during CVD, etc. is important for the formation of MX-type compounds (TiC, VC, etc.) having a sufficient film thickness. In other words, since dissolved C forms MX-type compounds especially by CVD surface treatment, carbon must be supplied from the steel, and an optimum amount of C depends on the amount of dissolved C present in the martensite structure before the steel is held at the surface treatment temperature. In the tool steel of the invention, the amount of dissolved C is not less than 0.4% and, therefore, sufficient film deposition is possible.

[0036] On the basis of the foregoing, the reasons for the selection of elements which constitute the tool steel of the invention and the limitation of the contents of these elements are described below.

[0037] For the C and Cr contents, the composition range shown in Figs. 1 and 2 is adopted from the standpoint of the similarity to JIS-SKD11 and from the feature that the amount of undissolved carbides just after hardening is not more than 5 mass %. Specifically, it is preferable for an improvement in machinability that the amount of carbides which are not in a solid solution state be not more than 5 mass % in a structure just after hardening at 1000° to 1050°C when calculated, for example, by a thermocalculator.

[0038] The heat treatment characteristics of JIS-SKD11 are such that size variation due to heat treatment in the rolling direction becomes minus in a region where the tempering temperature is not more than 490°C, whereas size variation due to heat treatment in the rolling direction turn to be plus side at a tempering temperature higher than 490°C. Further, another feature of the heat treatment characteristics of JIS-SKD11 is that the amount of maximum size variation due to heat treatment at a tempering temperature higher than 490°C becomes a plus value not more than 0.1%. At the same time, the heat treatment characteristics of SKD11 have also the feature that heat treatment conditions capable of obtaining a hardness in the range of from 57 to 60 HRC exist in these tempering regions.

[0039] The composition range that can meet all these features is shown in Figs. 1 and 2. The characteristic that the size variation on the minus side always occur at a temperature of not more than 490°C and that it turns to the plus side at a temperature higher than 490°C means that when treatment is performed by gradually raising the tempering temperature, such a condition as the amount of size variation due to heat treatment becomes zero surely exists somewhere. Therefore, it is possible to find out a heat treatment condition capable of making size variations close to zero. This accounts for the fact that JIS-SKD11 is supported by heat treatment engineers having high techniques, and provides the background of the de facto standardization of JIS-SKD11. Therefore, the balance between C and Cr shown here is especially important.

[0040] The Si content is also basically set on the basis of the similarity to JIS-SKD11 (Si = 0.25% by mass). Si is originally contained as a deoxidizer and for the purpose of improving castability, and toughness improves when the Si content is lowered. However, machinability deteriorates at the same time when the Si content is lowered and, therefore, it is necessary that the Si content be not less than 0.1%. On the other hand, an excessive amount of Si suppresses the precipitation of cementite, with the result that size variation due to heat treatment in a tempering region of 500 to 550°C increases. For this reason, the Si content is limited to the range of 0.1 to 0.6%.

[0041] The Mn content is also basically set on the basis of the similarity to JIS-SKD11 (Mn = 0.4% by mass). Although Mn is contained to improve hardenability, Mn contents of less than 0.1% are insufficient for obtaining quench hardness

in a stable manner. On the other hand, too high Mn contents cause a deterioration in weldability and further make the component segregation of matrix intensive as with Si. Therefore, the Mn content is limited to the range of from 0.1 to 1.2%. Incidentally, although Mn is an economic element that can replace expensive Cr, Mo, etc., no Mn may be added in a case where Cr, Mo, etc., fully exert their effects and where no S is added.

[0042] The Mo and W contents are also set on the basis of the similarity to JIS-SKD11 (Mo = 0.85% by mass). Mo and W improve hardenability. Moreover, softening does not occur rapidly even when tempering is performed on the high-temperature side. For this reason, hardness adjustments become easy. Because the atomic weight of W is about twice that of Mo, an Mo content of 1% has an effect equivalent to that of a W content of 2% and it is possible to express the effect by  $(Mo + 1/2W)$ . Either or both of Mo and W can be contained in the tool steel of the invention. In other words, the whole Mo content may be replaced with a W content which is twice the Mo content and a part of Mo may be replaced with an amount equivalent to the amount of Mo. The respect regarding which amount of  $(Mo + 1/2W)$  is preferentially used can be judged in consideration of cost effectiveness. However, it is desirable to add Mo because the replacement with W basically deteriorates flame hardenability.

[0043] When the amount of added  $(Mo + 1/2W)$  is less than 0.6%, a decrease in hardness by high-temperature tempering occurs abruptly and hardness control becomes difficult. On the other hand, excessive amounts of added  $(Mo + 1/2W)$  delay the precipitation and aggregation of the carbides in martensite, with the result that the size variation due to heat treatment by tempering at 500 to 550°C becomes great. The result is also such that due to the delayed decomposition of austenite associated with the delay in the tempering of martensite, unstable austenite is retained contrary to operators' expectations that thorough tempering must have been performed, thereby causing the size variation with the lapse of time to occur during the use of dies after the fabrication thereof. Therefore, the  $(Mo + 1/2W)$  content is limited to the range of from 0.6 to 1.25%. The  $(Mo + 1/2W)$  content is preferably 0.6 to 1.10%.

[0044] In the tool steel of the invention, the above composition may contain V when other effects is desired. The V content is also set on the basis of the similarity to JIS-SKD11 (V = 0.25% by mass). Although V is an element that increases the resistance to softening necessary for tool steels, it forms V-base carbides, thereby causing a decrease in machinability. Therefore, the V content is less than 0.5%.

[0045] Although S is disliked in the field of welding and high-hardness steels as a representative of elements causing embrittlement, it has the free-cutting effect. Therefore, it is possible to add S in an amount corresponding to an improvement in toughness which is achieved by a reduction in the amount of carbides. For this reason, the addition of S in amounts up to 0.2% is allowed while considering the fact that size variation due to heat treatment increases by the addition of S.

[0046] Ca is an ideal free-cutting element that does not cause a degradation in mechanical properties or structural deterioration. The free-cutting mechanism of this element lies in lowering the melting points of oxides dispersed in trace amounts in steel, with the result that these oxides melt with the heat of cutting, forming a protective film on the cutting edge. However, Ca is apt to come away from molten steel because of its high vapor pressure and, therefore, the addition of Ca in amounts up to about 100 ppm is made possible at most in the case of the present adding technique.

[0047] Rare earth elements may be contained in amounts of not more than 0.2% in order to improve the machinability of the tool steel of the invention. It is preferable that the total amount of incidental impurities be not more than 0.5%. However, it is possible to add Ni in amounts of not more than 5.0% when toughness and weldability are necessary. In addition, when it is necessary to impart further wear resistance to the tool steel of the invention, it is also possible to add Al in amounts of not more than 1.0%, thereby increasing hardness attained after nitriding. Moreover, the basic properties of the tool steel of the invention are not changed even if one or more elements selected from the group consisting of Pb, Se, Te, Bi, In, Be, Ce, Zr and Ti are added in an amount of not more than 0.2% for obtaining other desired effects.

[0048] According to the present invention, the adjusting of the condition after hardening is effective for further improving the effects of the present invention, that is, to adjust the amounts of dissolved C and Cr present in the martensite structure after hardening so that they may be close to those of JIS-SKD11 and to make the amount of residual carbides just after hardening not more than 5% by mass. This amount of residual carbides just after hardening can also be reduced in the steel manufacturing process. It is possible to reduce the amount of residual carbides just after hardening to not more than 5 mass % by adopting a powder method, a soaking method, which involves subjecting an ingot immediately after melting to heat treatment at a temperature of not less than 1100°C for about 1 to 10 hours, and a quenching solidification method and by reducing the size of an ingot. Further, it is also desirable for an improvement in machinability to reduce a Cr segregation range in matrix after hardening to not more than 1% by weight.

[0049] In the case of the above tool steel of the invention, it is possible to ensure a hardness of not less than 57 HRC in addition to excellent weldability, by performing hardening at 1000 to 1050°C and tempering at not less than 500°C under the same heat treatment conditions as in the conventional JIS-SKD11. Thus, in addition to the excellent machinability with a hardness of not less than 57 HRC, the tool steel of the invention is also excellent in surface treatment characteristics for the salt bath method and CVD treatment.

[0050] When the tool steel of the invention is used in dies, etc., flame hardening may be performed only in necessary

portions according to desired functions, or a heat treatment method for obtaining hardness may be selected while taking the number of production steps or required properties into consideration. For example, dies can be fabricated by tempering the tool steel of the invention to a hardness of not less than 55 HRC and performing cutting.

[0051] Another feature of the invention resides in the fact that a component makeup and a composition were found out which are sufficient for obtaining good mechanical properties, in particular, hardness and toughness although the content of C, which is the basic component of the tool steel, is reduced in comparison with JIS-SKD11, and that a tool steel excellent in weldability, machinability and surface treatment characteristics, i.e., heat treatment characteristics was achieved.

[0052] More specifically, in the tool steel of the invention, excellent weldability is ensured by reducing the C content and when this tool steel is used in dies, they can be easily reused because of the excellent toughness and because repairs by welding are easy even when breaks, cracks and wear occur during the use thereof. Besides, in order to cope with a case where wear resistance is insufficient due to reduced C contents, excellent surface treatment characteristics are also ensured.

[0053] In the present invention, the wording "to be excellent in weldability" or "welding is possible" means that welding cracks are not observed in the Y-shape test specified in JIS Z 3158 in which the prescribed preheating treatment and postheating treatment are performed. In welding, preheating and postheating are usually performed in order to prevent weld cracks during welding. Preheating is performed to prevent hot cracking during welding and postheating is performed to prevent cold cracking, the latter being a kind of tempering to lower the hardness of the weld heat-affected zone, in particular.

[0054] In general, dies are welded to make shape changes or are repaired depending on the condition during the manufacture or use thereof. In the case of dies of alloy steels, welding is performed when the dies are preheated to a high temperature in order to prevent cracking from occurring during welding. Especially, when dies contain Cr, etc., it is general practice to perform such welding after preheating to a temperature not lower than 450 to 550°C. According to the invention, however, it is possible to provide a tool steel in which weld cracks are not observed in the Y-shape test specified in JIS Z 3158 even when the preheating temperature is lowered to 250°C. For this reason, workability related to welding is improved and this steel is also economical.

[0055] Next, in high-carbon, high-chromium-base steels, postheating after welding is also important. In this case, the heating temperature and time for postheating can be reduced by decreasing the hardness of the weld heat-affected zone. Especially for the control of the weld heat-affected zone, it is effective to reduce the C content to not more than 0.75% and the Cr content to not less than 6.8%. This is effective in adjusting the amounts of C and Cr both dissolved in the martensite structure which have an effect on weldability.

[0056] Next, embodiments of the present invention are described in detail. However, the invention is not defined in any way by these embodiments.

Example 1:

[0057] First, materials were melted in a 100-kg high-frequency furnace and ingots with the chemical composition shown in Table 1 were made. The comparative material 1 is an equivalent to SKD11. Next, hot rolling was performed so that the forging ratio becomes about 5 and annealing at 850° for 4 hour was then performed after cooling.

Table 1

	Chemical composition (wt.%)									
	C	Si	Mn	S	Cr	Mo	W	V	Ca (ppm)	Fe
1	0.43	0.40	0.40	0.001	6.73	0.91	<0.01	0.10	-	Bal.
2	0.57	0.32	0.35	0.011	6.02	0.65	<0.01	<0.01	-	"
3	0.81	0.10	0.40	0.062	7.49	1.01	<0.01	<0.01	-	"
4	0.74	0.25	0.40	0.072	8.02	0.81	<0.01	<0.01	-	"
5	0.71	0.24	0.01	0.059	7.32	1.12	<0.01	0.25	55	"
6	0.69	0.68	0.35	0.060	7.15	0.89	<0.01	0.25	25	"
7	0.71	0.24	1.16	0.058	7.73	0.78	<0.01	<0.01	-	"
8	0.68	0.25	0.44	0.020	7.03	1.24	<0.01	0.23	-	"
9	0.60	0.60	0.46	0.021	6.89	0.44	<0.01	0.42	-	"
10	0.65	0.15	0.50	0.015	7.25	<0.01	2.4	<0.01	-	"

(to be continued)



Table 1 (continued)

Compara- tive materials	1	1.47	0.25	0.40	0.002	11.95	0.90	<0.01	0.35	-	Bal.
	2	0.95	0.30	1.05	0.001	0.75	-	0.75	-	-	"
	3	0.51	0.25	0.40	0.002	5.98	0.85	<0.01	0.25	-	"
	4	0.80	0.22	0.40	0.002	8.00	1.10	<0.01	0.25	-	"
	5	0.59	0.31	0.38	0.002	7.69	0.95	<0.01	0.25	-	"
	6	0.75	0.24	0.25	0.001	6.51	0.91	<0.01	0.24	-	"

(to be continued)

[0058] Next, 21 test pieces of 10 mm in diameter and 80 mm in length were fabricated for each material so that the rolling direction coincides with the longitudinal direction of the test pieces. After that, 10 pieces in the 21 test pieces were heated and held at 1025°C in a vacuum heating furnace, and gas cooling hardening in an inert gas was then performed. Moreover, tempering at 530°C for 1 hour was performed twice. The hardness of obtained test pieces was measured and it was found that in the comparative examples 2 and 3, the hardness is less than 57 HRC. Next, the length in the longitudinal direction of materials which showed hardness values of not less than 57 HRC was measured, a size variation was calculated on the basis of lengths before hardening, which had been measured beforehand, and an investigation was made as to how many test pieces with a size variation exceeding 0.1% occurred.

Table 2

	Number of test pieces with a size variation ratio exceeding 0.1%
Materials of the invention 1	0 piece
Materials of the invention 2	0 piece
Materials of the invention 3	0 piece
Materials of the invention 4	0 piece
Materials of the invention 5	0 piece
Materials of the invention 6	0 piece
Materials of the invention 7	0 piece
Materials of the invention 8	0 piece
Materials of the invention 9	0 piece
Materials of the invention 10	0 piece
Comparative material 1	0 piece
Comparative material 4	3 pieces
Comparative material 5	2 pieces
Comparative material 6	5 pieces

[0059] As is apparent from Table 2, the size variation was not more than 0.1% in all materials relating to the steel of the invention. In the comparative examples 4, 5 and 6, a size variation exceeding 0.1% occurred.

[0060] Next, in addition to the test pieces with a size variation of not more than 0.1% at 530°C, the remaining test pieces of comparative examples 4 and 5 in an annealed state were tested. Ten test pieces each were heated and held at 1025° in a vacuum heating furnace and gas cooling hardening in an inert gas was then performed. Moreover, tempering at 490°C for 1 hour was performed twice. After that, the length in the longitudinal direction of the test pieces was measured and a size variation was calculated on the basis of lengths before hardening, which had been measured beforehand. An investigation was made as to how many test pieces showed a size variation which increased on the plus side. The result of the investigation is shown in Table 3.

Table 3

	Number of test pieces with a size variation increasing at plus side
Materials of the invention 1	0 piece
Materials of the invention 2	0 piece
Materials of the invention 3	0 piece
Materials of the invention 4	0 piece
Materials of the invention 5	0 piece
Materials of the invention 6	0 piece
Materials of the invention 7	0 piece
Materials of the invention 8	0 piece
Materials of the invention 9	0 piece
Materials of the invention 10	0 piece
Comparative material 1	0 piece
Comparative material 4	0 piece
Comparative material 5	7 pieces

[0061] As is apparent from Table 3, the adjustment of size variations is difficult in the comparative example 5 because the size variation increases at the plus side, whereas size variations are easily adjusted and the same heat treatment as in JIS-SKD11 is possible in the examples of the invention 1 to 10 and the comparative example 1 because the size variation does not increase at the plus side in addition to the result shown in Table 2.

Example 2:

[0062] Next, machinability was evaluated.

[0063] First, the materials shown in Table 1 for which the behavior of size variation can be regarded as the same as with SKD11 in Example 1 (the materials of the invention 1 to 10 and comparative material 1) and the comparative material 4 were tested. These materials were brought into an annealed condition with a hardness of not more than 24 HRC and machinability was evaluated on a square end mill. The cutting test was performed under the conditions shown in Table 4. As is apparent from the result shown in Table 5, the materials of the invention 1 to 10 show high machinability with tool life (cutting edge wear: 0.3 mm) of not less than 10 m. In the comparative materials 1 and 4, machinability is inferior due to the presence of chromium-base carbides.

Table 4

Item	Conditions
Tool	2NKR10 (high-speed steel)
Cutting speed	25 m/min
Feed	0.08 mm/tooth
Depth of cut	0.8 x 1.5 mm
Cutting direction	Down cut
Cooling method	Dry type

Table 5

	Cutting length (service life) at cutting edge wear of 0.3 mm
Material of the invention 1	18 m
Material of the invention 2	18 m
Material of the invention 3	>20 m
Material of the invention 4	>20 m
Material of the invention 5	18 m
Material of the invention 6	>20 m
Material of the invention 7	>20 m
Material of the invention 8	18 m
Material of the invention 9	20 m
Material of the invention 10	18 m
Comparative material 1	<2 m
Comparative material 4	8 m

[0064] Next, from the materials for which the behavior of size variation can be regarded as the same as in JIS-SKD11 (the materials of the invention 1 to 10 and comparative material 1) and the comparative material 4, test materials adjusted to a hardness of 57 to 60 HRC by hardening at 1030°C and tempering at a temperature of not lower than 500°C were produced and machinability was evaluated on a square end mill. The cutting conditions adopted are shown in Table 6. From the test result shown in Table 7, it is apparent that the materials of the invention show good tool life (cutting edge wear: 0.1 mm) and high machinability, whereas the comparative materials 1 and 4 have inferior machinability.

Table 6

Item	Conditions
Tool	HES2100-C (cemented carbide coating)

Table 6 (continued)

Item	Conditions
Cutting speed	75 m/min
Feed	0.05 mm/tooth
Depth of cut	0.2 x 15 mm
Cutting direction	Down cut
Cooling method	Dry type

Table 7

	Cutting length (service life) at cutting edge wear width of 0.1 mm
Material of the invention 1	16 m
Material of the invention 2	14 m
Material of the invention 3	28 m
Material of the invention 4	24 m
Material of the invention 5	18 m
Material of the invention 6	26 m
Material of the invention 7	26 m
Material of the invention 8	22 m
Material of the invention 9	16 m
Material of the invention 10	16 m
Comparative material 1	<2 m
Comparative material 4	4 m

Example 3:

[0065] Ingots were made from some of the materials shown in Table 1, i.e., the materials of the invention 1 and 2 with relatively inferior machinability, the comparative material 1 with good heat treatment characteristics, and the comparative material 4. These ingots were soaked at 1160°C for 10 hours. After annealing, an adjustment to a hardness of 57 HRC was made by performing hardening at 1030°C and tempering at a temperature of not lower than 500°C. The machinability of these materials was tested. The test conditions shown in Table 8 were adopted and the cutting length to cutting edge wear of 0.1 mm was regarded as tool life. In addition, the characteristic X-ray of Cr on a 1-mm line of EPMA (electron probe X-ray microanalysis) of as-hardened materials was detected in order to evaluate the segregation of components of the matrix and a statistical analysis was also carried out by taking the amount of width variation of Cr present in locations other than carbides as 2σ. The results of the two tests are shown in Table 9.

Table 8

Item	Conditions
Tool	HES2100-C (cemented carbide coating)
Cutting speed	75 m/min
Feed	0.05 mm/tooth
Depth of cut	0.2 x 15 mm
Cutting direction	Down cut
Cooling method	Dry type

Table 9

	Cutting length (service life) at cutting edge wear width of 0.1 mm	Cr segregation range (%) in matrix
Material of the invention 1	28 m	0.8%
Material of the invention 2	28 m	0.8%

Table 9 (continued)

	Cutting length (service life) at cutting edge wear width of 0.1 mm	Cr segregation range (%) in matrix
Comparative material 1	<2 m	1.8%
Comparative material 4	6 m	2.5%

[0066] As is apparent from Table 9, although the materials of the invention in this example with a Cr segregation range as-hardened of not more than 1% show tool life that is further improved in comparison with the above examples, a no improvement in tool life could be expected in the comparative materials 1 and 4 due to segregation ranges of Cr exceeding 1%.

Example 4:

[0067] Materials were melted in a 50-kg high-frequency furnace and ingots with the chemical compositions shown in Table 10 were made. The comparative material 7 is an equivalent to SKD11. Next, hot rolling was performed so that the forging ratio becomes about 5 and annealing at 850°C for 4 hour was then performed after cooling.

Table 10

	Chemical composition (wt.%)									
	C	Si	Mn	S	Ni	Cr	Mo	W	V	Eutective Value: Z
11	0.55	0.25	0.41	0.005	0.2	6.52	0.98	-	0.25	8.31
12	0.75	0.30	0.35	0.100	0.004	7.91	0.35	1.05	0.25	10.35
13	0.70	0.25	0.56	0.072	0.01	7.41	1.05	-	0.25	10.05
14	0.71	0.59	0.71	0.030	0.21	7.01	1.01	-	0.25	9.89
15	0.69	0.25	0.23	0.030	2.51	6.83	0.98	-	0.24	9.16
16	0.73	0.24	0.41	0.025	0.11	7.12	0.61	-	0.21	10.11
17	0.71	0.26	0.39	0.025	0.12	7.21	1.19	-	0.26	10.01
18	0.68	0.27	0.40	0.024	0.10	7.42	1.01	-	0.49	9.89

(to be continued)

Table 10 (continued)

7	1.48	0.25	0.46	0.005	0.02	12.11	0.99	-	0.38	19.11
8	0.98	1.20	0.57	0.005	0.003	7.48	1.85	-	0.76	12.33
9	0.76	0.10	0.29	0.006	0.05	9.63	1.43	-	0.57	11.86
10	0.58	0.82	0.35	0.004	0.10	11.81	1.48	-	0.38	11.73
11	0.53	0.55	0.38	0.006	0.15	12.50	0.58	-	0.26	11.74
12	0.35	0.70	0.36	0.007	0.003	4.01	2.31	-	0.11	5.21
13	0.28	1.10	0.12	0.006	0.002	6.35	2.01	-	0.71	6.05
14	0.44	0.92	1.75	0.006	0.004	8.23	0.75	-	0.25	8.46
15	0.45	0.43	0.81	0.004	0.018	4.68	2.27	3.10	0.42	6.41
16	0.39	0.56	0.75	0.006	0.010	9.58	2.58	-	0.01	8.87
17	0.55	1.24	0.20	0.005	0.2	6.50	1.20	1.01	0.31	8.30
18	0.50	1.00	0.35	0.100	0.004	6.30	1.40	1.05	0.25	7.78

\* Material No. 12 of the invention further contains  
Ca of 71 ppm

[0068] Next, test pieces for the Y-shape test specified in JIS Z 3158 were taken from the above annealed materials. After heating and holding at 1025°C in a vacuum heating furnace, gas cooling hardening in an inert gas was performed. Subsequently, tempering was performed at 500 to 550°C so that the target hardness of each test piece became not less than 57 HRC. Test pieces thus prepared were welded under the conditions shown in Table 11 and weldability was evaluated. In the comparative materials 10 to 16, it was impossible to obtain hardness values of not less than 57 HRC by tempering at a temperature not less than 500°C.

Table 11

Item	Description
Preheating method	After charging into an electric furnace heated and held at a predetermined temperature, test pieces were held at the temperature for 1 hour.
Welding method	Arc welding
Electrode	Coated electrode equivalent to JIS Z3251 DF3B, electrode diameter: 4 mm
Welding current	110 A
Postheating method after welding	Test pieces were held at 450°C for 1 hour in the same manner as in the preheating.
Cooling time	7 hours
Method of judgment on weld cracks	From detecting test by the penetration and microscopic observation of internal cut sections

[0069] Weldability was evaluated according to whether cracks after welding exist or not. Table 12 shows the result of the evaluation, along with hardness values obtained by hardening and tempering. In the materials of the invention 11 to 18 and comparative materials 17 and 18, weld cracks did not occur even at a preheating temperature of 350°C. In the comparative materials 7, 8 and 9, cracks occurred at a preheating temperature of either 350°C or 450°C.

Table 12

	Hardness (HRC)	Preheating Temp. (°C)	Weldability (crack)
Material of the invention 11	59.9	350	no crack
Material of the invention 12	60.1	350	no crack
Material of the invention 13	59.5	350	no crack
Material of the invention 14	58.5	350	no crack
Material of the invention 15	59.7	350	no crack
Material of the invention 16	60.3	350	no crack
Material of the invention 17	60.2	350	no crack
Material of the invention 18	58.9	350	no crack
Comparative material 7	60.3	350	crack
Comparative material 8	59.8	450	crack
Comparative material 9	57.0	450	crack
Comparative material 17	59.0	350	no crack
	58.0	350	no crack
Comparative material 18	58.7	350	no crack
	60.0	350	no crack
Comparative material 17	59.9	450	no crack
Comparative material 18	60.1	450	no crack

Example 5:

[0070] Next, machinability was evaluated.

[0071] First, test materials with a hardness of not more than 24 HRC in an annealed state were prepared from the materials shown in Table 10 and the machinability on a square end mill was evaluated. Incidentally, the cutting test was performed under the conditions shown in Table 13. From the result shown in Table 14, it is apparent that tool life at least three times that of the comparative material 7, which is an equivalent to SKD11, can be obtained in the materials of the invention 11 to 18 and the comparative materials 17 and 18.



Table 13

Item	Conditions
Tool	2NKR10 (high-speed steel)
Cutting speed	40 m/min
Feed	0.08 mm/tooth
Depth of cut	0.8 x 1.5 mm
Cutting direction	Down cut
Cooling method	Dry type

Table 14

	Cutting length at cutting edge wear of 0.4 mm (service life)
Material of the invention 11	18 m
Material of the invention 12	>20 m
Material of the invention 13	20 m
Material of the invention 14	18 m
Material of the invention 15	16 m
Material of the invention 16	14 m
Material of the invention 17	18 m
Material of the invention 18	14 m
Comparative material 7	2 m
Comparative material 8	3 m
Comparative material 9	3 m
Comparative material 17	8 m
Comparative material 18	16 m

[0072] Next, test materials hardened and tempered under the heat treatment conditions of the invention to obtain a hardness of from 57 to 60 HRC were prepared from the materials shown in Table 10 and the machinability thereof on an square end mill was evaluated. The conditions are shown in Table 15. From the test result shown in Table 16, it is apparent that tool life at least six times that of the comparative material 7, which is an equivalent to SKD11, can be obtained in the materials of the invention 11 to 18 and the comparative materials 17 and 18.

Table 15

Item	Conditions
Tool	HES2100-C (cemented carbide coating)
Cutting speed	25 m/min
Feed	0.05 mm/tooth
Depth of cut	0.2 x 15 mm
Cutting direction	Down cut
Cooling method	Dry type

Table 16

	Cutting length at cutting edge wear width of 0.08 mm (service life)
Material of the invention 11	22 m
Material of the invention 12	32 m
Material of the invention 13	20 m
Material of the invention 14	18 m
Material of the invention 15	20 m

Table 16 (continued)

	Cutting length at cutting edge wear width of 0.08 mm (service life)
Material of the invention 16	16 m
Material of the invention 17	18 m
Material of the invention 18	20 m
Comparative material 7	3 m
Comparative material 8	10 m
Comparative material 9	12 m
Comparative material 17	22 m
Comparative material 18	32 m

Example 6:

[0073] Next, an investigation was made regarding the effect of the preheating temperature before welding and the cooling time after welding on weldability. In this investigation, test materials were obtained from the above annealed materials by performing heating and holding at 1025°C in a vacuum heating furnace, performing gas cooling hardening in an inert gas, and subsequently performing tempering at 500 to 550°C to a predetermined hardness. The postheating after welding was performed at 450°C and after holding at 1 hour, gradual cooling to room temperature was performed while spending a period of time of 3 hours or 7 hours. Table 17 shows the occurrence or non-occurrence of cracks under these conditions, along with hardness values and preheating temperatures.

Table 17

	Hardness (HRC)	Preheating Temp. (°C)	Cooling time (Hr)	Weldability (crack)
Material of the invention 11	57.3	250	3	no crack
Material of the invention 12	60.2	250	3	no crack
Material of the invention 13	59.5	350	3	no crack
Material of the invention 14	58.6	350	3	no crack
Material of the invention 15	59.3	350	3	no crack
Material of the invention 16	58.9	350	3	no crack
Material of the invention 17	58.0	350	3	no crack
Material of the invention 18	58.7	350	3	no crack
Comparative material 7	59.9	450	7	crack
Comparative material 15	54.8	450	7	crack
Comparative material 16	53.2	450	7	crack
Comparative material 17	59.2	250	3	no crack
	58.3	250	3	no crack
	58.7	350	3	no crack
Comparative material 18	60.0	350	3	no crack
	59.7	350	3	no crack
Comparative material	58.2	350	3	no crack

[0074] As shown in Table 17, although cracking occurred neither in the materials of the invention 11 to 18 nor in the comparative materials 17 and 18 even in a case where the cooling time of 3 hours was adopted, cracks were formed in the comparative materials 7, 15 and 16 even in the case of 7-hour cooling time.

Example 7:

[0075] Next, 10 test pieces 10 mm in diameter and 80 mm in length were prepared from each of the annealed materials of the invention 11 to 18 and annealed comparative materials 7 to 9, 17 and 18 so that the longitudinal direction of the test pieces coincides with the rolling direction. The longitudinal size of these test pieces before hardening

was measured beforehand and hardness was adjusted to 60 HRC  $\pm 1$  by performing air hardening after holding at 1030°C for 1 hour and by tempering at a temperature of not less than 500°C. After sufficient cooling of the test pieces at room temperature, the size was measured again, a size variation ratio relative to the size measured just before hardening was determined for each test piece, and the number of test pieces with a size variation ratio exceeding 0.1% was counted. The result is shown in Table 18.

Table 18

	Number of test pieces with size variation ratio exceeding 0.1%
Material of the invention 11	0
Material of the invention 12	0
Material of the invention 13	0
Material of the invention 14	1
Material of the invention 15	0
Material of the invention 16	0
Material of the invention 17	1
Material of the invention 18	0
Comparative material 7	0
Comparative material 8	10
Comparative material 9	4
Comparative material 17	10
Comparative material 18	10

[0076] As shown in Table 18, a size variation exceeding the limit was observed neither in the materials of the invention 11, 12, 13, 15, 16 and 18 nor in the comparative material 7, which is equivalent to SKD11. Even in the material of the invention 14 with a somewhat high Si content and the material of the invention 17 with a somewhat high Mo content, the number of test pieces with a size variation ratio exceeding 0.1% was 1 and small. In contrast to this, in the comparative materials 8, 17 and 18, size variations exceeding the limit occurred in all of the ten test pieces each because of high Si and Mo equivalents. Incidentally, although the comparative material 9 has a lower Si content than a tool steel as proposed in JP-A-11-181548, for example, size variations exceeding the limit occurred in four test pieces because of a high Mo equivalent.

[0077] Because in the steel of the invention, carbides are reduced in order to improve weldability and machinability, and there may occur such case as wear resistance is inferior when occasion demand. However, because the degree of freedom as to surface treatment is ensured owing to the size variation-reducing effect of the invention, it is possible to meet both the ease with which tools and dies are fabricated from the steel of the invention and the tool performance of the steel.

Example 8:

[0078] Next, in plate specimens with a size of 25 x 100 x 100 mm prepared from the annealed materials of the invention 11 to 18 and annealed comparative materials 7, 8, 9, 17 and 18, an investigation was made regarding size variation ratios in the rolling direction when TD treatment was actually performed. As the preheating treatment, hardening at 1020°C was performed and tempering at 530°C was performed twice. After that, finish working was performed and size in the rolling direction at 5 points were measured by changing places each time. Next, TD treatment at 1020°C for 7 hours was performed in order to generate VC for which the target film thickness was set at 3  $\mu$ m, and tempering at 530°C was performed twice. Besides, even in the postheating treatment, hardening was similarly performed at 1020°C and tempering was performed at 530°C. After that, sizes in the rolling direction were measured and the size variation ratio was calculated. The result is shown in Table 19.

Table 19

	Size variation ratio in the rolling direction (% , average value of 5 measurements)
Material of the invention 11	0.062
Material of the invention 12	0.054
Material of the invention 13	0.052

Table 19 (continued)

	Size variation ratio in the rolling direction (% , average value of 5 measurements)
Material of the invention 14	0.081
Material of the invention 15	0.042
Material of the invention 16	0.051
Material of the invention 17	0.079
Material of the invention 18	0.071
Comparative material 7	0.059
Comparative material 8	1.521
Comparative material 9	1.623
Comparative material 17	1.539
Comparative material 18	1.605

[0079] In the materials of the invention 11 to 18 and the comparative material 7 (an equivalent to SKD11), the size variation range is not more than 0.1% and is satisfactory. In the comparative materials 8, 9, 17 and 18, the size variation ratio greatly exceeds 0.1% and cannot bear practical use. The main reason why JIS-SKD11 has been widely used as a conventional die steel is that the heat treatment characteristics thereof are good. It is apparent that the steel of the invention has also such features as can be widely used. However, because materials equivalent to JIS-SKD11 are deficient in weldability and machinability as shown in Examples 4 and 5, it is apparent that the tool steel of the invention which is greatly improved in these points has a very high industrial value as a tool material.

Example 9:

[0080] Predetermined ingots were made from alloys with the chemical compositions shown in Table 20 melted in a high-frequency furnace. In Table 20, the comparative material 19 is an equivalent to JIS-SKD11. These ingots were forged at a forging ratio of 5 and finished to steel products, which were then annealed.

Table 20

No.	Chemical composition (wt.%) * Unit of Ca is ppm.										Amount of carbide $\geq 20\mu\text{m}^2$ (area %)	Amount of sulfide $\geq 1\mu\text{m}^2$ (area %)
	C	Si	Mn	S	Cr	Mo	W	V	Ca	Fe		
19	0.64	0.58	0.61	0.048	7.02	1.20	<0.01	0.22	-	Bal.	1.6	0.26
20	0.56	0.34	0.45	0.001	7.29	0.84	<0.01	0.34	-	"	1.0	-
21	0.62	0.33	0.31	0.064	7.59	0.63	<0.01	0.37	-	"	2.3	0.35
22	0.65	0.33	0.37	0.072	6.92	0.91	0.6	0.25	19	"	1.5	0.32
23	0.68	0.23	0.36	0.063	7.24	1.13	<0.01	0.28	32	"	2.1	0.26
24	0.72	0.25	0.29	0.135	7.37	1.25	<0.01	0.35	-	"	2.6	0.61
Steel of the invention												

(to be continued)

Table 20 (continued)

19	1.42	0.24	0.39	0.001	11.78	0.38	<0.01	0.23	-	"	10.6	-
20	0.72	1.05	0.45	0.061	8.19	1.22	<0.01	0.35	-	"	4.6	0.27
21	0.51	0.36	0.61	0.216	7.73	1.14	<0.01	0.37	-	"	1.4	0.98
22	0.63	0.39	0.42	0.029	7.03	0.62	<0.01	1.53	-	"	2.0	0.11
23	0.70	0.18	0.87	0.086	5.79	1.29	<0.01	0.18	-	"	1.9	0.36
24	0.43	0.31	0.12	0.058	6.90	0.74	<0.01	0.29	-	"	0.8	0.27
25	0.73	0.07	0.43	0.026	7.84	1.40	<0.01	0.36	-	"	2.3	0.11
26	0.70	0.27	0.39	0.053	8.03	1.71	0.92	0.22	25	"	3.5	0.25
27	0.81	0.23	0.34	0.062	7.26	0.88	<0.01	0.29	-	"	3.7	0.28
Comparative steel												

[0081] Next, after the above annealed materials were heated and held at 1030°C in a vacuum furnace, pressurized gas cooling hardening was performed, and tempering at 500 to 550°C was performed to obtain a target hardness of not less than 57 HRC. Incidentally, a hardness of not less than 57 HRC was not attained in the comparative material 24. The amounts of carbides and sulfides of these steel materials after the heat treatment were then measured. For measuring the amount of carbides, the sections of steel materials were polished and then etched in a 10% niter etchant, images within a field of view of 2 mm<sup>2</sup> under a microscope (a magnification of 200X) being taken into a computer, and the amount of carbides in a sectional area of not less than 20  $\mu\text{m}^2$  was determined with the aid of image analysis software. Sulfides were also analyzed in the same manner as with carbides. In this case, after the polishing of the sections of steel materials, sulfides in a sectional area of not less than 1  $\mu\text{m}^2$  were analyzed without etching. The results of the two analyses are shown in Table 20.

[0082] In each material of the invention, the area ratio of carbides in a sectional area of not less than 20  $\mu\text{m}^2$  is not more than 3%, and the area ratio of sulfides in a sectional area of not less than 1  $\mu\text{m}^2$  is not less than 0.2% in all materials of the invention except the steel 20. In contrast to this, the area ratio of carbides in a sectional area of not less than 20  $\mu\text{m}^2$  exceeds 3% in the comparative material 19, which is an equivalent to JIS-SKD11, and the comparative materials 20, 26 and 27.

[0083] In Table 21, there are shown measurement result of long axis/short axis ratio of sulfides each having a sectional area of not less than 1  $\mu\text{m}^2$  with respect to the materials in Table 20 having a forging ratio of 25 and 10R-notch Charpy impact test result regarding the same materials. In this case, the heat treatment conditions are the same as those mentioned above. The long axis/short axis ratio of sulfides was analyzed by the same method as in the measurement of sulfides shown in Table 20. In the materials of the invention 22 and 23, the long axis/short axis ratio is not more than 4.5 because of the effect of Ca, and a ratio of impact value in the direction vertical to forging extension direction to another impact value in the forging extension direction is high, and decrease in toughness in the direction vertical to the forging direction is suppressed in comparison with the comparative materials 20 and 27.

Table 21

No.		Long axis/short axis ratio of sulfides with sectional area not less than 1 $\mu\text{m}^2$	Ratio of 10R notch sharp impact value in a direction vertical to forging extension to another in forging extension direction
Steel of the invention	22	3.8	0.71
	23	4.1	0.63
Comparative steel	20	4.7	0.49
	27	5.1	0.39

Example 10:

[0084] Next, after the materials shown in Table 20 were subjected to heat treatment, Y-shape test specimens specified in JIS Z 3158 were prepared from these materials and weldability was evaluated by welding these test pieces under the conditions shown in Table 22. In this case, the same hardening and tempering conditions as in Example 9 were adopted. The hardness after hardening and tempering and the result of the weldability test are shown in Table 23.

Table 22

Item	Content
Preheating method	After charging into an electric furnace heated and held at a predetermined temperature, test pieces are held at the temperature for 1 hour.
Welding method	Arc welding
Electrode	Coated electrode equivalent to JIS Z3251 DF3B, electrode diameter: 4 mm
Welding current	110 A
Postheating method after welding	Test pieces are held at 450°C for 1 hour in the same manner as with preheating.
Cooling time	Spending 7 hours
Method of judging weld cracks	Dye penetration flaw detecting test and microscopic observation of internal cut sections

Table 23

No.		Hardness after hardening and tempering (HRC)	Weldability test result	
			Preheating temp. (°C)	Weldability (crack)
Steel of the invention	19	58.5	350	no crack
	20	58.3	350	no crack
	21	58.2	350	no crack
	22	58.4	350	no crack
	23	57.9	350	no crack
	24	58.5	350	crack
	24	58.5	450	no crack
Comparative steel	19	58.8	450	crack
	20	58.1	450	crack
	21	57.6	450	crack
	22	57.9	450	crack
	23	58.6	450	crack
	24	56.7	450	no crack
	25	58.0	450	no crack
	26	58.7	450	crack
	27	58.1	450	crack

[0085] In all materials of the invention, hardness of not less than 57 HRC was obtained by tempering at a temperature of not lower than 500°C, and the heat treatment characteristics were almost the same as with SKD11. In contrast to this, hardness of not less than 57 HRC was not achieved in the comparative material 24. As for weldability, no crack occurred in the materials of the invention when the preheating temperature was 450°C. However, weld cracking occurred in the comparative material 19 which is equivalent to JIS-SKD11 due to high C and Cr contents, in the comparative material 20 due to a high Si content, in the comparative material 21 due to a high Cr content, besides, a high S content, in the comparative material 22 due to a high V content, in the comparative material 26 due to a high (Mo + 1/2W) content, and in the comparative material 27 due to a high C content. Conversely, weld cracking occurred in the comparative material 23 due to a low Cr content.

Example 11:

[0086] Next, machinability was evaluated. Test pieces with a size of 50 mm x 100 mm x 200 mm were prepared from the materials with the chemical compositions shown in Table 20 in an annealed state (hardness: about 15 HRC), and the machinability on a square end mill was evaluated under the conditions shown in Table 24. In conducting the evaluation, the cutting length until the wear of the cutting edge of tool becomes 0.3 mm was regarded as tool life. The result is shown in Table 25.

Table 24

Item	Description
Tool	High-speed steel two-flute end mill, tool diameter: 10 mm
Cutting speed	16.5 m/min
Feed rate	0.08 mm/tooth
Manner of cutting	0.8 mm x 10 mm



Table 24 (continued)

Item	Description
Cutting direction	Down cut
Lubrication	Wet type

Table 25

No.	Cutting length (m) until cutting edge wear becomes 0.3 mm
Steel of the invention	19 >20
	20 20
	21 18
	22 >20
	23 >20
	24 20
Comparative steel	19 2
	20 6
	21 18
	22 12
	23 >20
	24 >20
	25 10
	26 8
	27 8

[0087] It is apparent that the materials of the invention have better machinability than the comparative material 19 which is equivalent to JIS-SKD11. In the comparative materials 19, 20, 26 and 27 with a high C or Cr content, whose area ratio of carbides with a sectional area of not less than  $20 \mu\text{m}^2$  after hardening and tempering exceeds 3%, the area ratio of carbides is high even in an annealed state, with the result that the machinability thereof becomes inferior. The comparative material 22 is inferior in machinability because its V content is high and, besides, the area ratio of sulfides is low even in an annealed state. On the other hand, the comparative material 25 is inferior in machinability because, its Si content is low and the area ratio of sulfides is also low.

[0088] Further, after the materials of the chemical compositions shown in Table 20 in an annealed state were heated and held at  $1030^\circ\text{C}$  in a vacuum furnace, pressurized gas cooling hardening was performed, and hardness was adjusted to about 58 HRC by tempering at a temperature of not less than  $500^\circ\text{C}$ . Machinability was evaluated under the conditions shown in Table 26. Incidentally, in evaluating machinability, a cutting length until the wear of the cutting edge of the tool becomes 0.1 mm was regarded as tool life. The result is shown in Table 27.

Table 26

Item	Description
Tool	Cemented carbide two-flute coating end mill, tool diameter: 10 mm
Cutting speed	75 m/min
Feed rate	0.05 mm/tooth
Manner of cut	0.2 mm x 15 mm
Cutting direction	Down cut
Lubrication	Dry type

Table 27

No.		Hardness (HRC)	Cutting length (m) until cutting edge wear becomes 0.1 mm
Material of the invention	20	58.1	>20
	22	57.9	18
Comparative material	19	58.0	2
	20	58.3	10

[0089] It is apparent from Table 27 that the materials of the invention have good machinability even in a hardened and tempered state, and that this machinability is much better than that of the comparative material 19, which is equivalent to SKD11. The comparative material 20 is also inferior in machinability to the materials of the invention, because this comparative material has a high Cr content and its area ratio of carbides with a sectional area of not less than 20  $\mu\text{m}^2$  exceeds 3%.

Example 12:

[0090] Next, a test was conducted to examine size variation due to heat treatment. From each of the materials with the chemical compositions shown in Table 20 in an annealed state, 20 test pieces with a size of 10 mm in diameter and 60 mm in length were prepared. After these test pieces were heated and held at 1030°C in a vacuum furnace, pressurized gas cooling hardening was performed, and tempering at 530°C for 1 hour was performed twice. After that, sizes in the longitudinal direction were measured and size variations relative to the size measured just before hardening were evaluated. Table 28 shows the number of test pieces with a size variation ratio of not less than 0.2%.

Table 28

No.		Number of test pieces with a size variation ratio of not less than 0.2%
Material of the invention	19	0
	20	0
	21	0
Comparative material	19	0
	20	11
	26	8

[0091] In all materials of the invention, size variations due to heat treatment are less than 0.2%. Thus, their heat treatment characteristics are almost equal to those of the comparative material 19, which is equivalent to JIS-SKD11. It is apparent, however, that the comparative material 19 is inferior in weldability and machinability as in Examples 10 and 11 and that the materials of the invention have excellent properties. On the other hand, size variations of not less than 0.2% due to heat treatment occurred in a large number of test pieces in the comparative material 20 because of a high Si content and in the comparative material 26 because of a high Mo equivalent.

Example 13

[0092] In this example, by using the materials 6, 8, 25 and 26 of the invention shown in Table 29, hardness attained by nitriding was researched. The materials 25 and 26 were prepared by adding aluminum into the materials 6 and 8, respectively. These steels were prepared by a process having the steps of: performing the retaining at 1030°C in a furnace, performing the cooling and hardening by use of pressurized gas; and performing tempering at 500 to 550°C so that a target hardness value may become not less than 57 HRC. After that, ion nitriding treatment was performed in which the materials were held at 520°C for 5 hours in an atmosphere of hydrogen, nitrogen and argon having a volume ratio of 1:1:2, respectively. The hardness was measured at a location inwardly distant 0.025 mm in depth from the surface of each of the materials by use of a Vickers' Hardness Tester with testing force of 2.942 N. The results of the measurement are shown in Table 30. As apparent from Table 30, the hardness of nitrided materials are raised by adding aluminum.

Table 29  
Composition of the steels of the invention (mass %)

No.	C	Si	Mn	S	Cr	W	Mo	V	Ca	Al	Fe
6	0.69	0.68	0.35	0.060	7.15	0.89	<0.01	0.25	25*	-	remainder
25	0.71	0.65	0.38	0.056	7.28	0.82	<0.01	0.22	23	0.39	remainder
8	0.68	0.25	0.44	0.020	7.03	1.24	<0.01	0.23	-	-	remainder
26	0.71	0.28	0.39	0.024	6.98	1.18	<0.01	0.26	-	0.13	remainder

\* ppm

Table 30

No.	Hardness after nitriding (Hv 0.3)
Steel of the invention 6	1082
Steel of the invention 25	1241
Steel of the invention 8	1057
Steel of the invention 26	1134

[0093] As mentioned above, according to the present invention, it is possible to provide a steel material which has better machinability in an annealed state than JIS-SKD11 and also has high toughness and weldability in connection with the material performance after hardening and tempering. Further, because the steel of the invention has characteristics which are close to JIS-SKD11 with respect to all of size variations due to heat treatment, hardenability and hardness change caused at the tempering temperature, it is possible to feed this steel into the same furnace as SKD11, increasing productivity and making it unnecessary to treat the steel under special conditions setting.

[0094] In addition, the machinability of the steel of the invention after hardening and tempering is much higher than that of JIS-SKD11, and film characteristics do not deteriorate even in surface treatment which is greatly affected by the amount of dissolved C present in the steel, such as CVD. Therefore, this steel can be easily manufactured as a die material with excellent wear resistance. Thus, the present invention has high industrial value.

#### Claims

1. A tool steel with excellent weldability, machinability and heat treatment characteristics, consisting, by weight, of: C and Cr in both of which  $(Cr + 5.9 \times C)$  is 9.1 to 12.5,  $(Cr - 4.2 \times C)$  being not more than 5 and  $(Cr - 6.3 \times C)$  being not less than 2.2; 0.1 to 0.6 % Si; not more than 1.2 % Mn; at least one of Mo and W of not more than 1.25 % in total in terms of  $(Mo + 1/2W)$ ; less than 0.5 % V; and the balance Fe and incidental impurities.
2. The steel of claim 1, wherein the  $(Mo + 1/2W)$  content is 0.6 to 1.10 %, the Mn content is 0.1 to 1.2 %, the Si content is 0.1 to 0.3 % and the V content is 0.05 to less than 0.5 %.
3. The steel of claim 1, wherein the eutectic value  $Z [= 8 \times (C\%) + 0.6 \times (Cr\%)]$  is not more than 10.8.
4. The steel of claim 1, wherein the C content is 0.55 to 0.75 % by weight and the Cr content is 6.8 to 8.0 % by weight.
5. The steel of claim 4, wherein eutectic value Z is not less than 9 and not more than 10.5.
6. The steel of any preceding claim, wherein the area ratio of carbides with a sectional area of not less than  $20 \mu m^2$  to the section of the structure is not more than 3 %.
7. The steel of any preceding claim, wherein the S content is not more than 0.2 % by weight, preferably 0.005 to 0.12 % by weight.
8. The steel of any one of claims 1 to 6, wherein the Ca content is not more than 100 ppm by weight.
9. The steel of claim 7 or 8, wherein the area ratio of sulfides with a sectional area of not less than  $1 \mu m^2$  in the section of the structure is not less than 0.2 % and, preferably, not more than 0.7 %.
10. The steel of any one of claims 7 to 9, wherein, regarding sulfides with a sectional area of not less than  $1 \mu m^2$  in the section of the structure, the long axis/short axis ratio of the length of each sulfide is not more than 4.5.
11. The steel of any preceding claim, wherein the Ni content is not more than 5.0 % by weight, preferably not more than 1.0 % by weight.
12. The steel of any one of claims 1 to 9, wherein Cr segregation range in matrix after hardening is not more than 1 % by weight.

EP 1 072 691 A2

13. The steel of any preceding claim, having a maximum hardness of not less than 57 HRC after hardening at 1000 to 1050 °C and tempering at a temperature of not less than 500 °C.
- 5 14. The steel of any preceding claim, wherein the size variation due to heat treatment by tempering at a temperature of not less than 500 °C is not more than 0.1 % relative to the size measured just before hardening in terms of linear expansion coefficient, and the size variation due to heat treatment by tempering at 490 °C is not more than 0.
- 10 15. The steel of any one of claims 1 to 11, wherein the Al content is not more than 1.0 % by weight, preferably not more than 0.6 % by weight.
16. The steel of any preceding claim subjected to soaking treatment at 1000 to 1400 °C.
- 15 17. A die produced by tempering the steel of any preceding claim to a hardness of not less than 55 HRC and cutting the steel.

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FIG.1

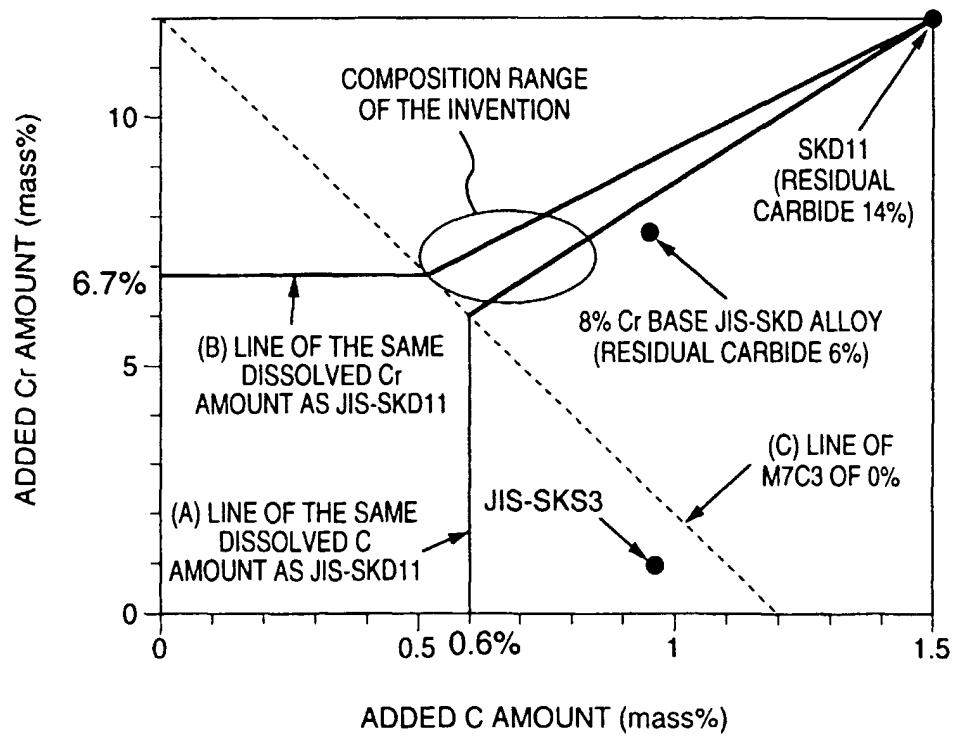


FIG.2

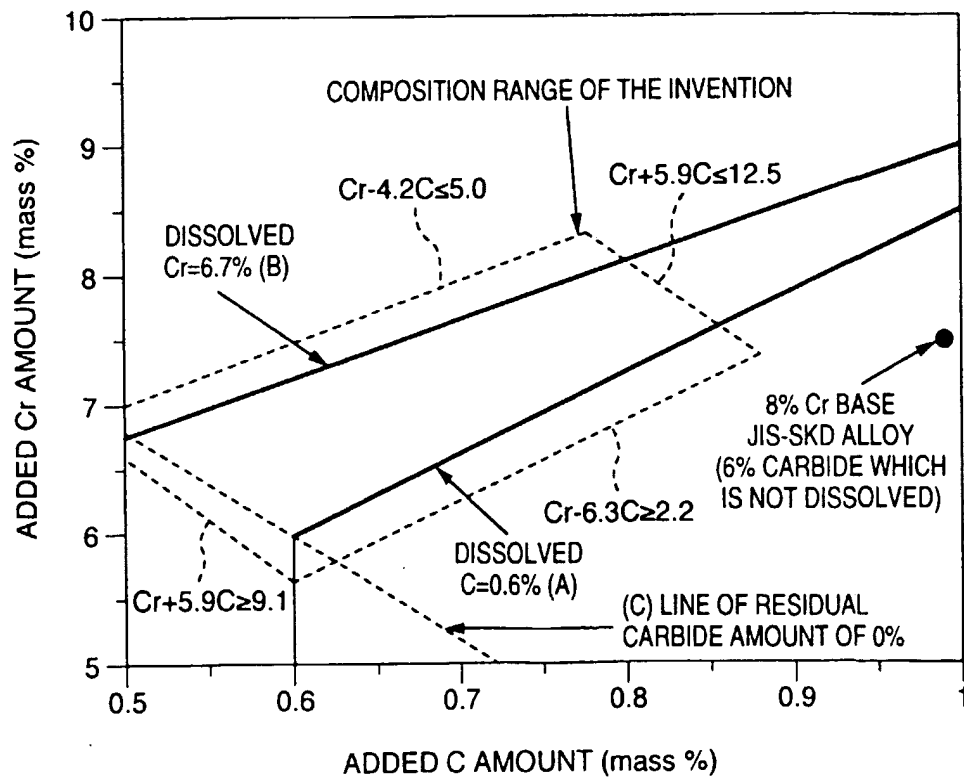


FIG.3

